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Optimal siting of electric vehicle charging stations: A GIS-based fuzzy Multi-Criteria Decision Analysis

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A B S T R A C T

Electric vehicles (EVs) are both economic and ecological vehicles which get their power from rechargeable batteries inside the car. Since they have a lot advantages as producing nearly no carbon emissions or pollution, being cost effective and less noisy; the main disadvantage of these vehicles are recharge related problems. One approach to deal with this problem is to construct electric vehicle charging stations (EVCS). A proper EVCS also should be located very carefully to maximize EV usage. Thus in this paper a geographic information system (GIS)-based MCDA approach is applied to address the EVCS site selection. Fuzzy analytical hierarchy process (AHP) and technique for order preference by similarity to ideal solution (TOPSIS) methods are applied to choose the optimal EVCS sites. A four-step solution approach is developed for the problem: (*i*) determination of 15 criteria from different perspectives, (*ii*) using GIS to assign EVCS site availability score, (*iii*) prioritizing the criteria using fuzzy AHP and finally (*iv*) ranking the potential sites by using TOPSIS. Proposed hybrid methodology is applied to Ankara (capital city of Turkey) as a case study. Results show that suggested alternative locations outperform the current locations of 12 EVCS in terms of considered criteria.

1. Introduction

Electric vehicles are transport vehicles that use one or more electric motors or traction motors for propulsion. An EV may be powered through a collector system by electricity from off-vehicle sources, or may be self-contained with a battery or generator to convert fuel to electricity [1]. When the energy challenge in the world is examined, this option seems to be a promising one for the future. If the gas prices do not fall down, people will look for alternative energies. In some countries, the cost of petroleum products forces people to use public transportation or to walk. Many people now prefer EVs instead of fossil-fuel vehicles because EVs are cheaper to drive and they are eco-friendly [2]. The cost of charging an electric car costs less than the cost of a full tank. EVs can potentially emit substantially lower CO_2 emissions than internal combustion engine vehicles [3,4]. In addition, the cost of brand new EVs has dropped over ten years.

According to the Electric Vehicle World Sales Database, worldwide EV sales including June is 312,000, 49% higher than for the same period in 2015 (Fig. 1). The total vehicle market is up by 5% in the first half year to 35 million vehicles and 12 million trucks. EV sales grow 10 times faster than the overall market, but still have a world market share of below 1%. China is the main reason for the high growth. With current regional growth rates, China will stand for 50% of electric vehicle sales by the end of the year [6]. According to a study of International Energy Agency, the vehicle sales will steer up to 7 million and global market share will be 9% according to the forecasts [5].

There are generally 3 main types of EV charging namely; conductive charging, inductive charging and battery replacement [4]. In conductive charging method, the battery is connected by a cable and plugged directly into an electricity provider. But the inductive method, works through an electromagnetic transmission without any contact between the EV and the charging station. The third method is replacing the discharged batteries with new batteries in a station. But in this method, the dimensions and internal connections of the batteries should be standardized. Thus, this method is the least used method. Currently, the automotive

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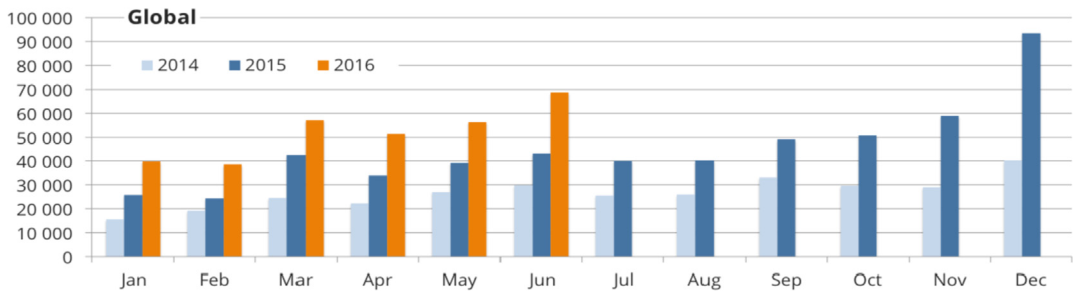

Fig. 1. Global EV sales [5].

industry and charging stations operators choose conductive charging because it is much cheaper and more efficient [7].

There are a lot of benefits of EVs. For example, energy efficiency, EVs convert a higher rate of electrical energy from the grid to power but gasoline vehicles convert less energy of gasoline to power. EVs are eco-friendly; they do not pollute the air or make too much noise. Electric motors provide quiet, smooth operation and stronger acceleration, also they require less maintenance. They reduce energy dependence on petroleum products by turning to electricity which is a domestic energy source [8].

Due to aforementioned benefits, Turkey's Ministry of Industry and Trade has been studying the trend towards electric and hybrid-powered vehicles and aims to make the country a leading EV manufacturer. Incentives are granted by the government for EV manufacturers and investments are made in R&D. Another important adjunct, the "charging stations" will be introduced, while agreements and special arrangements will be made with electric distributors and oil stations [9]. The Turkish government has devoted considerable resources to promote the adoption of EVs, and has set up a target of putting 45,000 EVs on the road by 2020 at a compound annual growth rate of 98.9% [10]. Meanwhile, a significant amount of investment has been made to subsidize EV manufacturers and buyers, build charging stations and posts, and offer tax breaks. For example, twelve Original Equipment Manufacturers (OEMs) are expected to launch their EV models and also public charging stations in next five years. Turkey had 203 charging stations in 2016 and 120,000 more are expected to be installed by 2020. Fig. 2 shows the distribution of 203 EVCSs in Turkey. As it can be seen from Figs. 2 and 147 of these stations are located in İstanbul, representing approximately 72% of all stations.

Of course there are some disadvantages of EVs and most important of which is the short driving ranges. Recharge time of the vehicle is generally long, for example recharging the battery can take 4–8 h. Also the battery packs are expensive and heavy [12]. Therefore, the availability of efficient, convenient and economic EVCSs could enhance the EV purchase request of consumers and assist the development of the sector. Low availability of charging infrastructure could hinder EV adoption, which could then in turn reduce incentives to invest in charging infrastructure development [13]. EVCS siting is the preliminary stage of EVCS construction, and has a significant impact on the service quality and operation efficiency of EVCSs during their whole life cycle. Therefore, it is essential to establish a proper framework to determine the optimal sites for EVCSs [14].

Finding a suitable site for an EVCS requires a multi-criteria approach and high levels of accuracy and reliability in the maps [15]. The effectiveness of final decision is clearly dependent on the quality of the data that are used to produce the criteria maps. Herein, Geographic Information System-based Multi-Criteria Decision Analysis (GIS-based MCDA) methodology helps converting spatial and non-spatial data into information within decision maker's own judgement [16].

In this paper, a scientific and strategic decision-making methodology is applied to determine new potential locations for EVCSs. To do so, a four step approach is developed. Firstly, the evaluation criteria for optimal siting of EVCSs which covers three dimensions and 15 sub-criteria are determined. Secondly, the geographic information of each indicator is mapped by using GIS software to

Fig. 2. 203 EVCSs in Turkey [11].

assign an EVCS siting availability score to each site. In the last two steps, indicators are prioritized by fuzzy AHP and potential EVCS sites are ranked by using TOPSIS techniques. Using real data from the city of Ankara, the validity of our evaluation approach is tested and then the best alternative locations obtained from the proposed method and the current 15 EVCSs are compared. It should be noted that the proposed method is not only applicable to Ankara but all cities that can consolidate the related data for our model.

The paper is organized as follows: next section reviews the literature for similar studies. Third section defines the attributes that help to choose the optimum places in detail. Fourth section handles our proposed GIS-based Fuzzy MCDA approach for EVCS site selection while the fifth section examines a case study for Ankara. Last section summarizes the study and gives directions for future research.

2. Literature review

Over the last decade, many studies related to the benefits, influence and technology of the EV industry have been conducted by several researches such as Nansai et al. [17] and Wang et al. [18]. The reader is referred to the comprehensive survey by Malczewski [19] for a recent coverage of the state of the art on EVCS site problems and solution approaches [20]. In the EV literature, there are a lot of papers which cover a wide study area such as designing the frequency-droop controller of plug in EVs [21]; assessment of the technical impact of EVs [4]; fast frequency control and synthetic (virtual) inertia control [22] and routing of EVs [23]. Besides mentioned studies, research focused on siting of EVCSs, which we also focus on, has received much more attention in recent years. Studies on EVCS siting and sizing problems with different solution methodologies are summarized in Table 1. It can be seen that almost all the researches related to the site selection of EVCS employed a type of decision-making method, such as integer programming [24], mixed integer programming [25,28], genetic algorithm [31,37], particle swarm optimization [29], ant colony optimization [26], chemical reaction optimization [30] and data envelopment analysis [33].

However, it is a known fact that EVCS site selection is a multiple-criteria evaluation problem as it is influenced by various conflicting criteria, which leads to the fact that the decision success depends mainly on the MCDA method. Thus, several MCDA are applied to EVCS siting problem over last years. Tang et al. [15] evaluate EVCS site locations in consideration of traffic factors, economic factors, social factors and influencing factors associated with a total of 13 sub-criteria. They use fuzzy AHP to determine the weights of each main and sub-criteria. A later study which divided the criteria into four categories: criteria related to offer, criteria related to demand, other relevant criteria and the dynamic evaluation criteria is proposed by Raposo et al. [32] to determine location of EVCSs. PROMETHEE method is applied to 4 main and 7 sub-criteria. In addition to mentioned MCDA methods, fuzzy TOPSIS is applied to an EVCS siting problem which consists of environmental, economic and social criteria associated with a total of 11 sub-criteria by Guo and Zhao [34]. Although their proposed approach is tested on a case study, the data of the case study are ignored. Finally, different MCDA methods are combined to evaluate EVCS site selection by Wu et al. [35] and Zhao and Li [14]. The former combines PROMETHEE and ANP approaches in terms of economic factors, engineering feasibility, service availability, social, environmental and land factors; whereas the latter propose a fuzzy Delphi and GRA-VIKOR combination on economy, society, environment and technology criteria. The main drawback of aforementioned studies which use MCDA approaches is lack of incorporation between spatial data and evaluation criteria. Because, siting of EVCSs is a spatial decision problem which typically involves a large set of feasible alternatives and multiple, conflicting and incommensurate evaluation criteria. Two distinctive areas of research, GIS and MCDA can benefit from each other to overcome the intersections between spatial data and evaluation criteria. On the one hand, GIS has an important role to integrate of spatially referenced data in a problem solving environment. On the other hand, MCDA provides a rich collection of techniques and procedures for structuring decision problems, and designing, evaluating and prioritizing alternative decisions [19].

GIS-based MCDA techniques are commonly used for different spatial decision problems in literature such as wind power plant site selection [38], municipal landfill site selection [39], freight village site selection [40] and refugee camp site selection [41]. Although there are many studies which apply GIS-based MCDA approach on spatial decision problems as mentioned above, there is still a gap on selection of EVCS sites.

In view of this, this paper employs GIS-based fuzzy MCDA approach to determine the optimal site of EVCS from environmental/geographical, economic and urbanity perspectives. Fuzzy AHP and TOPSIS methods are applied as MCDA approach to assign the weights to criteria and rank the alternative locations under uncertainty. This paper contributes to the literature in several ways: (*i*) proposing a four step GIS based fuzzy MCDA approach −to the best knowledge of the authors it is the first application on EVCS site selection−, (*ii*) presenting a framework using 15 different spatial data connected with environmental/geographic, economic and urban indicators, (*iii*) providing an analytic tool by offering new locations and comparing with current stations.

3. Analysis of evaluation attributes

An advisory board including academicians (authors) and four experts is constructed to determine and assess the dimensions affecting the location of an EVCS. Four experts are industrial engineers and are serving for Schneider Electric Co. located in Manisa. The company helps to power the future of sustainable mobility with EVCSs and infrastructure solutions in all cities of Turkey. The authors are entrusted to search the literature and find the related criteria. After the interview with the experts and literature review, 15 different sub-criteria are determined. Then, determined 15 criteria are grouped under 3 main dimensions: environmental/geographical, economic and urbanity criteria (Fig. 3).

Table 2 shows considered criteria with their relation in the literature and a brief description of each criterion. As it can be seen on Table 2, most of the authors considered distance to vegetation and water resources, land cost and service area population criteria predominantly [14,15,34,35]. However, it must be noted that proximity to petrol stations, distance to other EVCSs, possibility of expansion and earthquake risk criteria are also important to select a location for an EVCS as some authors indicated or suggested. To do so, a comprehensive criteria pool is selected to evaluate EVCSs in this study.

4. GIS-based fuzzy MCDA approach for EVCS site selection

The procedure to calculate the available EVCS locations is presented in Fig. 4.

The first step of the process is to determine the 15 criteria which are mentioned in the previous section. Alternative locations based on each criterion are designated by using GIS in the second step. GIS data obtained from different sources are used to perform spatial analysis via ESRI ArcGIS 10.2 software. In GIS analysis part of this study, spatial analysis such as Euclidean distance, inverse distance weighted (IDW), slope and weighted overlay are used to find out the optimum location for EVCSs. Euclidean distance analysis

Table 1
Studies on EVCS site selection.

References	Detail of study	Solution methodology	Application type
Wang [24]	Considering type of recharge time, fleet size, locating capacity, cost, and mean length of stay at destinations to economically determine the optimal locations to be located at destinations for electric scooters	Integer programming	Case study in Penghu
Frade et al. [25]	Maximal covering model to study the location of EVCS and to define the number and capacity of EVCS	Mixed integer programming	Case study in Lisbon
Phonrattanasak and Nopbhorn [26]	Proposing an optimal location of EVCS on residential distribution grid aiming to minimize annual cost of power line loss, travelling cost of EVs in recharging, investment cost and variable cost of operation	Ant colony optimization	Case study in Tianjin
Tang et al. [15]	Evaluation of EVCS site locations in terms of transportation, economy, society and effect criteria associated with a total of 13 sub-criteria	Voronoi Diagram Fuzzy AHP	Theoretical study
Liu et al. [27]	Optimal siting of EVCSs by a two-step screening method with environmental factors and service radius of EVCSs	Primal-dual interior point algorithm	Theoretical study
Chen et al. [28]	Determining optimal location assignments of EVCS, which minimized the station access cost of EV users and took the parking demand, local job, population density and trip attributes as constrains	Mixed integer programming	Case study in Seattle
Pashajavid and Golkar [29]	Allocating charging station of EVs to minimize energy loss and voltage deviation in the distribution system	Particle swarm optimization	Theoretical study
Lam et al. [30]	Formulating the EVCS placement problem and proving the problem as NP-hard	Mixed integer programming Greedy approach Chemical reaction optimization	Case study in Hong Kong
You and Hsieh [31]	Installing alternative charging stations on suitable locations to provide recharging services and maximize the number of people who can complete round-trip itineraries	Mixed integer programming Genetic algorithm	Theoretical study
Raposo et al. [32]	Evaluation of EVCS site locations in terms of criteria related to offer, criteria related to demand, other relevant criteria and the dynamic evaluation criteria associated with a total of 7 sub-criteria	PROMETHEE	Case study in Angra do Heroísmo
Khalkhali et al. [33]	Determining the optimal size and location of EVCS to maximize the distribution system manager benefit	Data envelopment analysis	Theoretical study
Guo and Zhao [34]	Evaluation of EVCS site locations in terms of environmental, economic and social criteria associated with a total of 11 sub-criteria	Fuzzy TOPSIS	Case study in Beijing
Wu et al. [35]	Evaluation of EVCS site locations in terms of economic factors, engineering feasibility, service availability, social factors, environmental factors and land factors criteria associated with a total of 15 sub-criteria	PROMETHEE ANP	Case study in Beijing
Zhao and Li [14]	Evaluation of EVCS site locations in terms of economy, society, environment and technology criteria associated with a total of 37 sub-criteria	Fuzzy Delphi Method Fuzzy GRA-VIKOR	Case study in Beijing
Gagarin and Corcoran [36]	Modeling the facility location problem of the placement of charging stations in road networks as a multiple domination problem on reachability graphs.	k-dominating sets	Case study in Boston and Dublin
Jordan et al. [37]	Evaluation of EVCS site locations considering data from heterogeneous sources such as traffic, social networks, population, etc.	Genetic algorithm, multi-agent systems	Case study in Spain
Proposed study	Evaluation of EVCS site locations in terms of environmental/geographic, economic and urbanity criteria associated with a total of 15 sub-criteria	Geographic information system Fuzzy AHP TOPSIS	Case study in Ankara

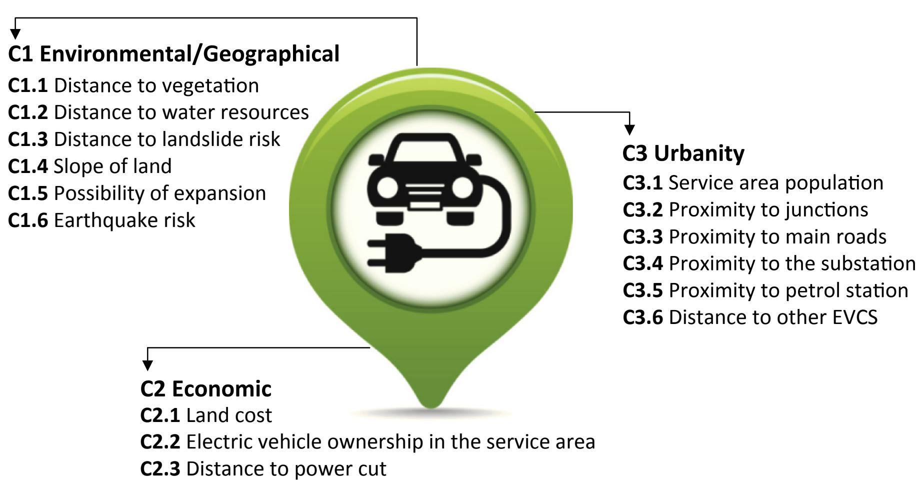

Fig. 3. Criteria architecture of EVCS siting.

calculates the straight-line distance of the each point to the closest source. This analysis is used to calculate distance and proximity values of criteria. IDW technique -which is a type of interpolation that calculates the degree of relationship between points-is used to calculate public land and poverty density. Slope analysis identifies the slope in percent of the land. Based on the C1.4 criterion, available areas with less than 7% slope are determined by slope analysis. Each pixel on the ArcGIS is equal to a minimum of 256 m^2 (16×16) m^2 which provides the adequate acreage and possible expansion (satisfying C1.5 criterion). In order to ensure measurement

Table 2
Place and definition of evaluation criteria in the literature.

Criteria	Definition	[1]	[2]	[3]	[4]	[5]	[6]
Environmental Geographical Criteria	C1.1 The construction of EVCS may have adverse effects on vegetation, so EVCS should be away from vegetation	√	√	√	√		√
	C1.2 The construction of EVCS may have adverse effects on water resources, so EVCS should be away from vegetation	√	√	√	√		√
	C1.3 The EVCS should not be located on landslide hazard zones			√		√	√
	C1.4 The EVCS should be located on an area which is flat (e.g.no greater than 7%)			√		√	√
	C1.5 Expansion of the charging station should be possible if needed in the future			√			√
	C1.6 The EVCS should be located on out of earthquake zones					√	√
Economic Criteria	C2.1 The land cost of EVCS charging station should not be high to minimize the total costs of establishment	√	√	√	√		√
	C2.2 EV ownership in the service area should be high to ensure that many owners get access to the charging service		√	√	√		√
	C2.3 The EVCS should be located on an area away from the locations experiencing frequent power cut	√		√	√		√
Urbanity Criteria	C3.1 Refers to the number of EV that can get access to the charging service provided by EVCS		√	√	√		√
	C3.2 The EVCS location should be near to junctions to maximize the amount of cars that get the service		√	√	√		√
	C3.3 The EVCS should be near to main roadways to keep the vehicles working	√		√	√	√	√
	C3.4 The ideal location of the charging station should be close to the substations		√	√	√		√
	C3.5 The ideal location of the charging station should be near to petrol stations, because hybrid vehicles use petroleum products						√
	C3.6 The ideal location of the charging station should not be very near to other EVCS						√

Sources: **[1]** Tang et al. [15]; **[2]** Guo and Zhao [34]; **[3]** Wu et al. [35]; **[4]** Zhao and Li [14]; **[5]** Çetinkaya et al. [41]; **[6]** *Proposed paper*.

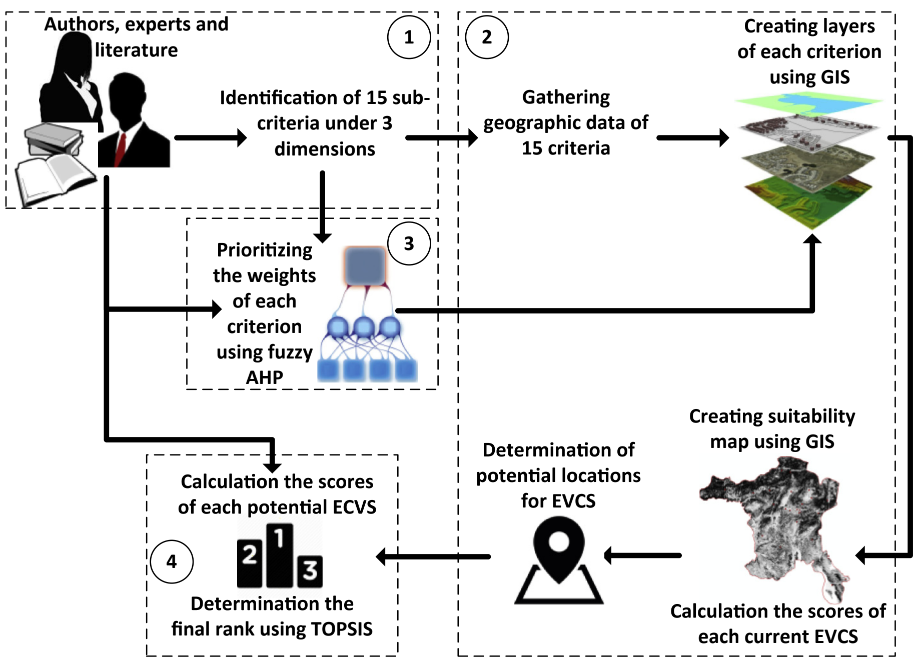

Fig. 4. Applied methodology (adapted from Ref. [41]).

integrity, the results of all are normalized after conducting the analysis. Then, all analyses are combined to select the alternative locations for EVCSs using the spatial analysis software, ArcGIS 10.2. The next step is to calculate the weight values of GIS layers. The calculation of the weight values is conducted by the application of the fuzzy AHP to include vagueness for experts' judgments. Alternative locations for EVCSs are obtained multiplying the weights obtained by fuzzy AHP and normalized spatial values obtained by GIS. Finally, determined alternative locations are ranked by using TOPSIS in the last step.

5. Optimal EVCS site selection: A case study in Ankara

This section presents the results of the proposed methodology on a city. After obtaining the initial solutions, different modifications are applied on the methodology to provide managerial insights.

5.1. Application area

The study area, Ankara, is the capital of Turkey and the country's second largest city. The city has a mean elevation of 938 m and in 2017 had a population of 5,445,351 with its total acreage of 25,437 km^2. The city is an important commercial and industrial city in Turkey and it is located at 39° 52′ 30″ North, 32° 52′ East. According to International Energy Agency, Ankara Metropolitan Municipality has also announced that it will acquire a fleet of 100 EVs. Initially, the charging stations will be located at the municipality buildings. The next step will be to install charging stations on different locations of Ankara. Therefore, Ankara is selected as the

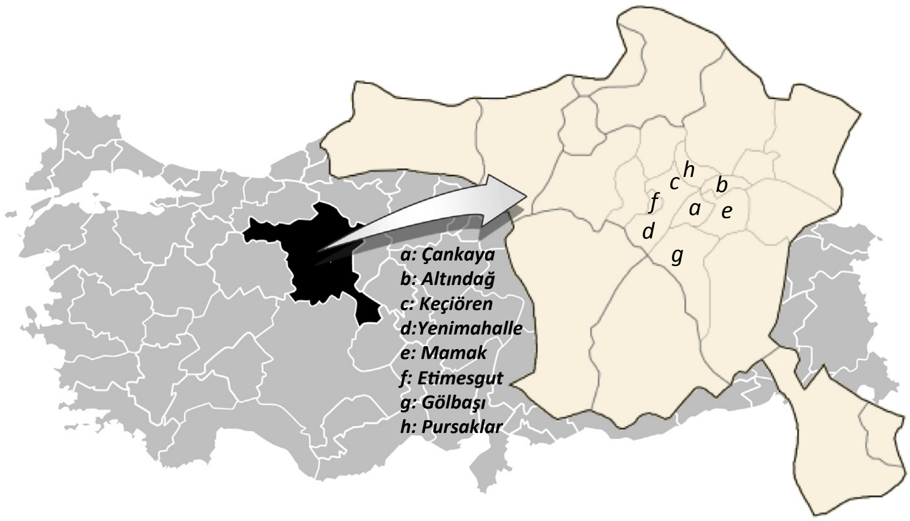

Fig. 5. Study area with 8 districts of Ankara.

case study in this paper. Due to having highest population, 8 districts of Ankara (also center of Ankara), namely *Çankaya*, *Altındağ*, *Keçiören*, *Yenimahalle*, *Mamak*, *Etimesgut*, *Gölbaşı* and *Pursaklar* are taken into account (Fig. 5).

5.2. The data set and layers of GIS

The geographic values of each criterion are obtained using ArcGIS ESRI software. Table 3 describes the GIS data type for each criterion. In order to ensure measurement integrity, the geographic data of each criterion are normalized between 0 and 1. While 1 is represented in the figure by a completely white color, a completely black color represents 0. Thus, the favorable areas are illustrated in white. Fig. 6 shows map layers of each criterion with normalized values. Data for each criterion is available for upon request.

After normalization, the layers are combined and the alternative locations for EVCSs are obtained. Due to non-visualization of possible expansion criterion, it is not illustrated in Fig. 6. It is assumed that the weights of each criterion are equal while GIS is determining the alternative locations. Due to lack of compatibility with the desired criteria, some locations are not preferable. Fig. 7 shows the availability of locations for EVCSs according to normalized and classified values.

EVCS suitability map in Fig. 7 indicates that the East part of Ankara has the highest rate for EVCS settlement. On the contrary, South of Ankara has the lowest rate. In the next section, weights of criteria are calculated by using fuzzy AHP to determine candidate locations. The AHP, introduced by Saaty [42]; is a structured technique for organizing and analyzing complex decisions. It deals with complex decision making, and can support the decision maker to set priorities, rank alternatives and make the best decision [42].

5.3. Determination of the priorities by using fuzzy AHP

In this phase, the experts are given the task of forming an individual pairwise comparison matrix by using the scale given in Table 4. *Superdecision* software is used to create the hierarchic structure of the evaluation criteria (Fig. 8). It is noted that the inconsistency ratio, which means the user makes the evaluations consistently, is smaller than 0.1. Geometric means of these values are found to obtain the pairwise compassion matrix on which there is a consensus.

Criteria under the goal are paired, and the following question is presented to the decision-making team: “Which is considered more important by the experts in selecting the EVCS location, and how much more important is it with respect to satisfaction with the EVCS location?” The experts select one criterion and then determine its degree of importance according to the scale in Table 4. The

Table 3
Spatial data and analysis list.

Criteria		Data	Data Source	Analysis
C1.1	Distance to vegetation	Forest	International vector data	Euclidean dist.
C1.2	Distance to water	Rivers, lakes	International vector data	Euclidean dist.
C1.3	Distance to landslide	Landslide areas	General Directorate of Mineral Research and Exploration	Euclidean dist.
C1.4	Slope	Shuttle radar topography mission	U.S. Geological Survey	Slope
C1.5	Possibility of expansion	–	–	–
C1.6	Earthquake risk	Active faults	General Directorate of Mineral Research and Exploration	Euclidean dist.
C2.1	Land cost	Text	Turkish Statistical Institute	IDW
C2.2	EV ownership	Vehicle count	Turkish Statistical Institute	Kernel Density
C2.3	Distance to power cut	Text	Başkent EDAŞ (Electricity Distribution Inc. of Ankara)	Euclidean dist.
C3.1	Service area population	Counties, population	Turkish Statistical Institute	Kernel Density
C3.2	Proximity to junctions	Junctions	General Command of Turkey	Euclidean dist.
C3.3	Proximity to main roads	Roadway	General Command of Turkey	Euclidean dist.
C3.4	Proximity to the substation	Substations	The Chamber of Electrical Engineers of Turkey	Euclidean dist.
C3.5	Proximity to petrol station	Petrol stations	http://www.firmasec.com/firma/ara/benzin-istasyonu/ankara/	Euclidean dist.
C3.6	Distance to other EVCS	EVCS	http://www.bdoto.com/; http://www.esarj.com	Euclidean dist.

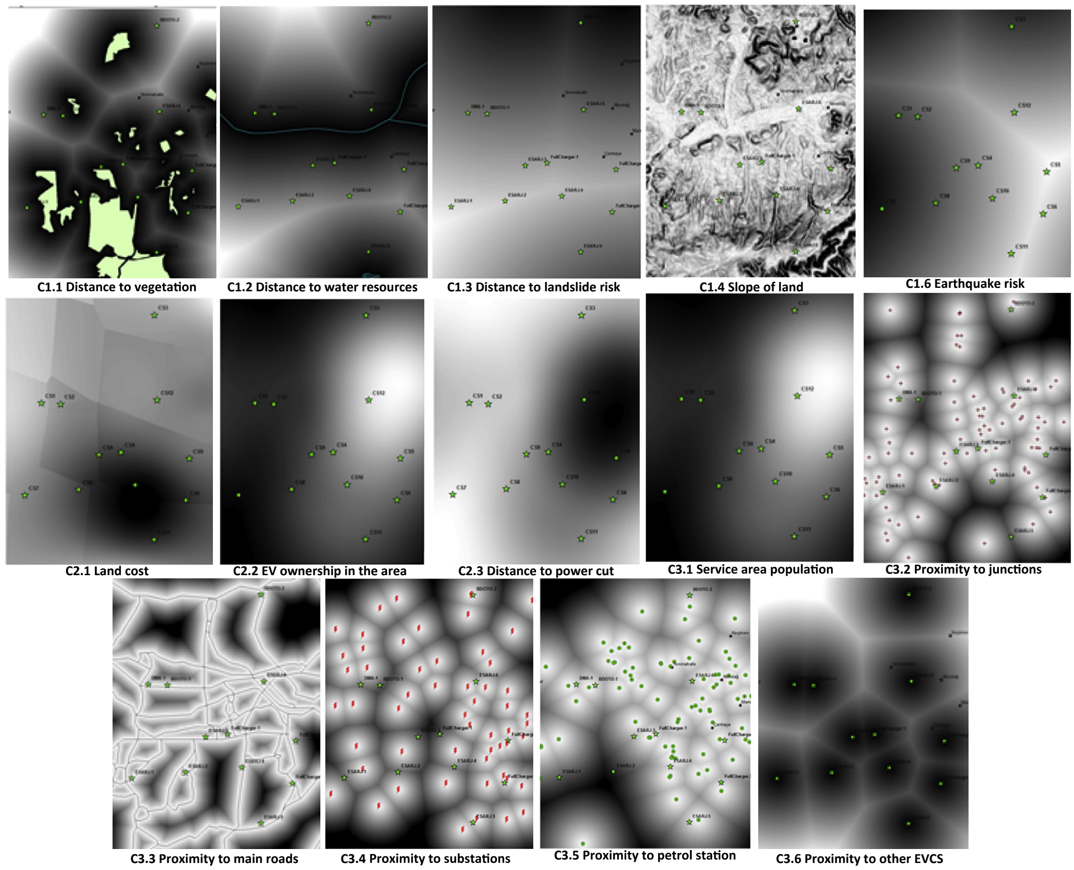

Fig. 6. GIS layer of each criterion.

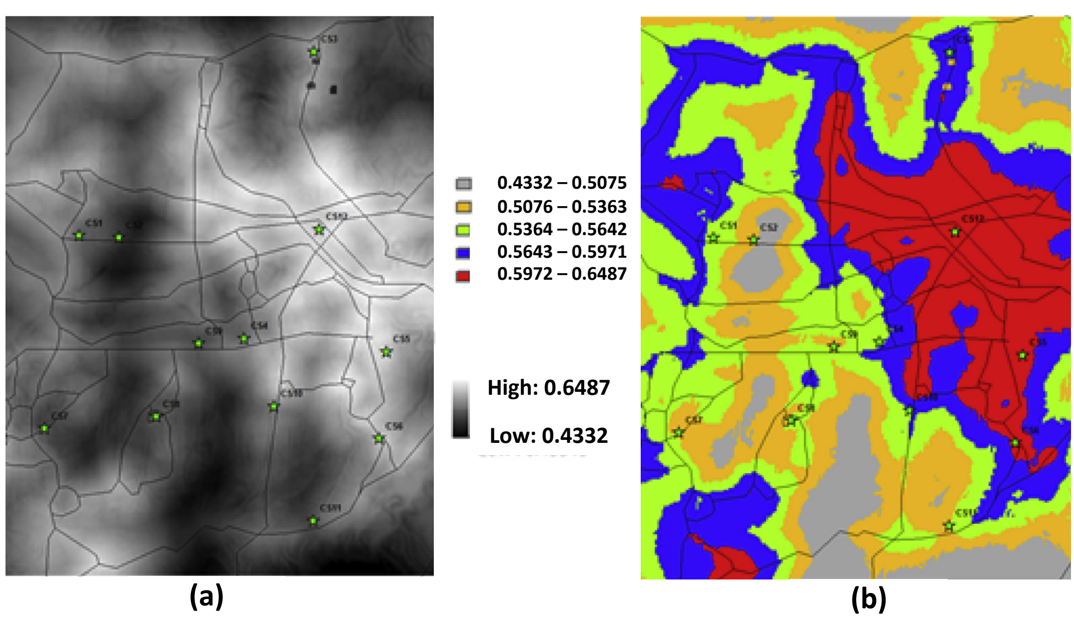

Fig. 7. EVCS site suitability map (a) normalized and (b) classified values.

same process is applied for each of the other criteria. The pairwise comparison matrices for main criteria and sub-criteria of urbanity criteria are given in Tables 5 and 6 together with the calculated weights. All calculated scores of the criteria weights are defuzzified through COA (center of area) defuzzification method [44]. The COA is used as a defuzzifier for all output variables of the developed models. In COA defuzzification, the crisp value is taken to be the geometrical center of the output fuzzy value, where the output fuzzy value is formed by taking the union of all fuzzy rule contributions [45].

Table 4
Comparison scale [43].

Linguistic scale for importance	Abbreviation	Triangular fuzzy scale	Triangular fuzzy reciprocal scale
Equal importance	EI	(1, 1, 1)	(1, 1, 1)
Weak importance (of one over the other)	WI	(2, 3,4)	(1/4, 1/3, 1/2)
Strong importance	SI	(4, 5, 6)	(1/6, 1/5, 1/4)
Demonstrated importance over the other	DI	(6, 7, 8)	(1/8, 1/7, 1/6)
Absolute importance	AI	(8, 9, 10)	(1/10, 1/9, 1/8)

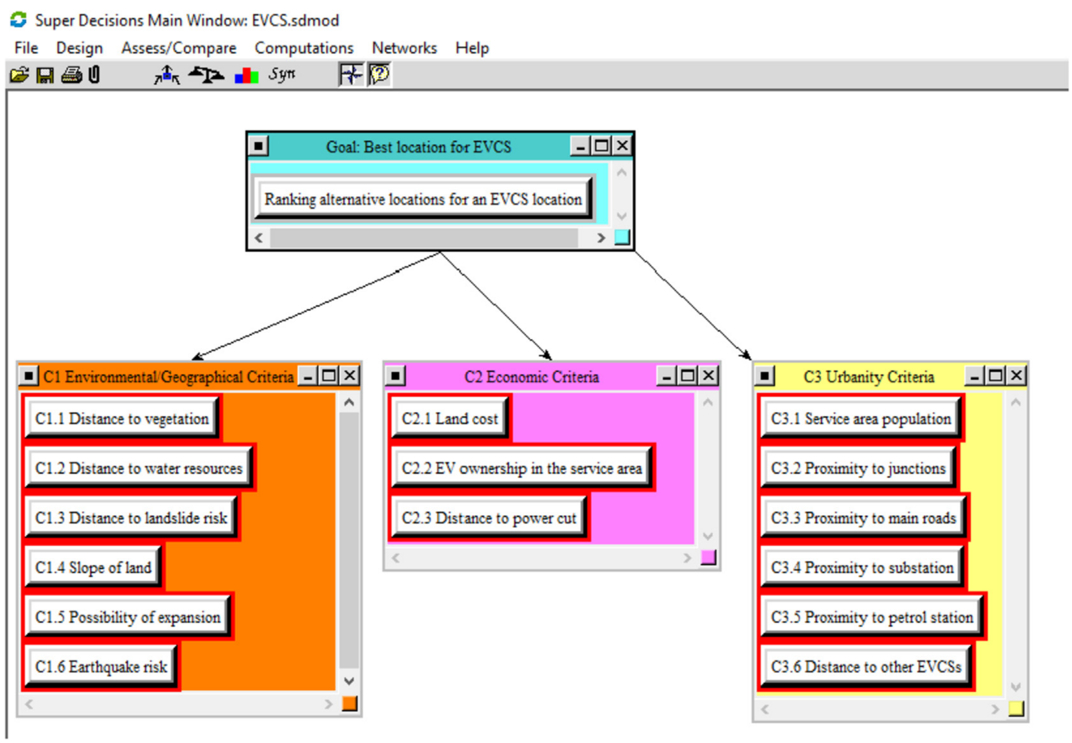

Fig. 8. The hierarchic structure of the criteria evaluation.

Table 5
Weights and pairwise comparison matrix of main criteria.

	C1			C2			C3			Weight		
	l	m	u	l	m	u	l	m	u	l	m	u
C1	1.00	1.00	1.00	0.35	0.44	0.55	0.38	0.49	0.63	0.159	0.188	0.219
C2	1.82	2.27	2.88	1.00	1.00	1.00	1.26	1.44	1.59	0.411	0.463	0.518
C3	1.59	2.03	2.62	0.63	0.69	0.79	1.00	1.00	1.00	0.312	0.349	0.398

Table 6
Local weights and pairwise comparison matrix of urbanity criteria.

	C31			C32			C33			C34			C35			C36			Weight		
	l	m	u	l	m	u	l	m	u	l	m	u	l	m	u	l	m	u	l	m	u
C31	1.00	1.00	1.00	2.52	3.56	4.58	1.26	1.44	1.59	2.88	3.98	5.04	6.00	7.00	8.00	4.00	5.00	6.00	0.281	0.342	0.398
C32	0.22	0.28	0.40	1.00	1.00	1.00	0.48	0.58	0.72	3.63	4.72	5.77	4.58	5.59	6.60	2.88	3.98	5.04	0.150	0.184	0.223
C33	0.63	0.69	0.79	1.39	1.71	2.08	1.00	1.00	1.00	6.60	7.61	8.62	6.60	7.61	8.62	6.00	7.00	8.00	0.283	0.320	0.361
C34	0.20	0.25	0.35	0.17	0.21	0.28	0.12	0.13	0.15	1.00	1.00	1.00	4.58	5.59	6.60	0.55	0.69	0.91	0.053	0.063	0.076
C35	0.13	0.14	0.17	0.15	0.18	0.22	0.12	0.13	0.15	0.15	0.18	0.22	1.00	1.00	1.00	0.35	0.44	0.55	0.025	0.029	0.034
C36	0.17	0.20	0.25	0.20	0.25	0.35	0.13	0.14	0.17	1.10	1.44	1.82	1.82	2.27	2.88	1.00	1.00	1.00	0.051	0.061	0.074

Weights of sub-criteria in Table 6 are defuzzified by COA method and crisp weights are obtained after normalization. Final weights obtained by fuzzy AHP are shown in Table 7. Results of crisp AHP are also given in the table to be used in scenario analysis. In terms of main criteria, economic dimension outweighs in other dimensions with priority value of 0.462. According to Table 7, the most important factor is "EV ownership in the service area" from the economic criteria group. With an overall priority value of 0.197, this

Table 7
Weights of criteria obtained by AHP and fuzzy AHP.

Main and Sub-criteria	Crisp	Fuzzy	Main and Sub-criteria	Crisp	Fuzzy
C1 Environmental/Geographical Criteria	0.188	0.187	**C3 Urbanity Criteria**	0.349	0.351
C1.1 Distance to vegetation	0.022	0.109	**C3.1** Service area population	0.120	0.109
C1.2 Distance to water resources	0.024	0.022	**C3.2** Proximity to junctions	0.062	0.059
C1.3 Distance to landslide risk	0.057	0.053	**C3.3** Proximity to main roads	0.108	0.102
C1.4 Slope of land	0.030	0.028	**C3.4** Proximity to substation	0.026	0.020
C1.5 Possibility of expansion	0.013	0.011	**C3.5** Proximity to petrol station	0.011	0.009
C1.6 Earthquake risk	0.043	0.039	**C3.6** Distance to other EVCSs	0.021	0.020
C2 Economic Criteria	0.463	0.462			
C2.1 Land cost	0.104	0.094			
C2.2 EV ownership in the service area	0.217	0.197			
C2.3 Distance to power cut	0.142	0.128			

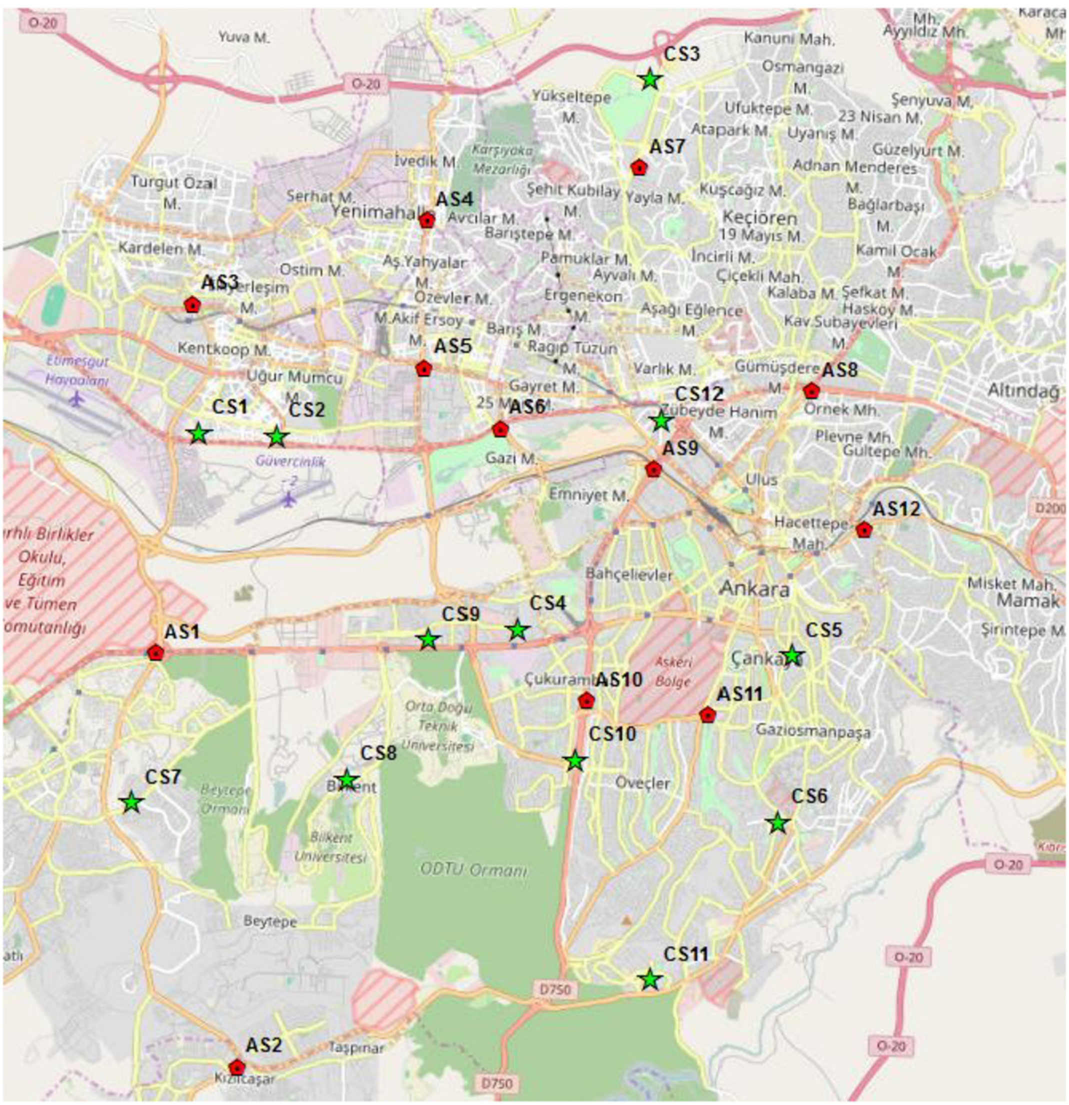

Fig. 9. 12 alternative and current EVCSs.

aspect should be considered the most important of the criteria. Other considerable factors are ranked as follows: "Distance to power cut" (weight is 0.128), "Distance to vegetation" (0.109) and "Service area population" (0.109). The lowest priority values belong to "Proximity to petrol station" (0.009) and followed by "Possibility of expansion" (0.011).

5.4. Ranking the alternative locations using TOPSIS

By using the weights in Table 7, the best 12 alternative locations with highest score values are determined for an EVCS. To do so, all candidate locations are compared by satellite images and the ones inside the residential area, river, forest, and highway are not selected as candidate EVCS. The reason of choosing 12 alternative locations is making a fair comparison with current 12 EVCSs. Selected 12 alternative stations (AS) and current stations (CS) are illustrated in Fig. 9. Detailed information (technical properties, their status and coordinates) about current stations can be found at https://esarj.com/harita.

TOPSIS method is applied to rank the alternative stations (AS1 to AS12) which are shown in Fig. 9. TOPSIS is a method of compensatory aggregation that compares a set of alternatives by identifying weights for each criterion, normalizing scores for each criterion and calculating the geometric distance between each alternative and the ideal alternative, which is the best score in each criterion. That the technique uses both negative and positive criteria makes the decision making easier [46]. The readers can find the detail formulation of applied TOPSIS method in Hwang et al. [46]. Alternatives' performance values according to the sub-criteria are shown in Table 8. Scores and ranking are determined by using TOPSIS as shown in Table 9. All calculations of TOPSIS are conducted using Microsoft Excel. According to Table 9, the best location for an EVCS is AS9, while the worst location is the AS1. Possible reasons for A9's high ranking are its (*i*) EV ownership in the service area, (*ii*) service area population and (*iii*) earthquake risk. If one ideal location is to be selected, then AS9 should be chosen because it possesses the highest C_i value. As a summary, the flow of application process is shown in Fig. 10.

5.5. Scenario analysis and managerial insights

In this section the results of three different scenario analyses are presented to provide managerial insights. The former presents three different cases which compare alternative and current stations based on three approaches namely GIS-based fuzzy AHP-TOPSIS (proposed approach), GIS-based TOPSIS (alternative approach 1) and GIS-based AHP-TOPSIS (alternative approach 2)

Table 8
Alternatives' performance values according to the sub-criteria based on TOPSIS.

Locations	Sub-criteria														
	C11	C12	C13	C14	C15[a]	C16	C21	C22	C23	C31	C32	C33	C34	C35	C36
AS1	0.032	0.286	0.745	0.971	1.000	0.144	0.705	0.118	0.887	0.113	0.986	0.986	0.841	0.921	0.461
AS2	0.389	0.642	0.734	0.947	1.000	0.438	0.667	0.035	0.951	0.036	0.984	0.982	0.303	0.969	1.000
AS3	0.281	0.375	0.387	0.960	1.000	0.471	0.837	0.178	0.841	0.172	0.984	0.975	0.916	0.661	0.549
AS4	0.038	0.543	0.259	0.990	1.000	0.539	0.673	0.260	0.842	0.259	0.993	0.990	0.961	0.822	0.409
AS5	0.204	0.252	0.411	0.993	1.000	0.632	0.673	0.304	0.796	0.303	0.980	0.985	0.940	1.000	0.147
AS6	0.167	0.138	0.483	0.969	1.000	0.672	0.654	0.490	0.596	0.490	0.981	0.982	0.948	0.883	0.049
AS7	0.227	0.425	0.221	0.995	1.000	0.404	0.680	0.608	0.599	0.608	0.509	0.982	0.939	0.970	0.546
AS8	0.110	0.059	0.399	0.979	1.000	0.702	0.563	0.982	0.031	0.982	0.984	0.975	0.670	0.972	0.394
AS9	0.167	0.049	0.504	0.982	1.000	0.797	0.632	0.872	0.136	0.873	0.978	0.982	0.850	0.850	0.078
AS10	0.145	0.376	0.753	0.992	1.000	0.695	0.185	0.593	0.353	0.603	0.940	0.985	0.969	0.998	0.065
AS11	0.015	0.442	0.745	0.928	1.000	0.857	0.288	0.626	0.243	0.635	0.982	0.980	0.931	0.986	0.196
AS12	0.131	0.093	0.545	0.971	1.000	0.894	0.616	0.771	0.079	0.772	0.984	0.984	0.878	0.880	0.414

[a] Each pixel on the ArcGIS is equal to a minimum of 256 m^2 (16 × 16) m^2 which provides the adequate acreage and possible expansion (satisfying C1.5 criterion) for each alternative location.

Table 9
Final ranking for alternative locations based on TOPSIS.

	Alternative Locations											
	AS9	AS8	AS7	AS12	AS6	AS10	AS11	AS2	AS5	AS3	AS4	AS1
S_i-	0.1024	0.1116	0.0851	0.0904	0.0715	0.0732	0.0727	0.0884	0.0680	0.0743	0.0605	0.0593
S_i+	0.0649	0.0742	0.0587	0.0731	0.0729	0.0763	0.0890	0.1089	0.0859	0.0952	0.1029	0.1166
C_i*	0.6122	0.6006	0.5916	0.5528	0.4950	0.4898	0.4497	0.4480	0.4421	0.4383	0.3704	0.3371
Rank	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**

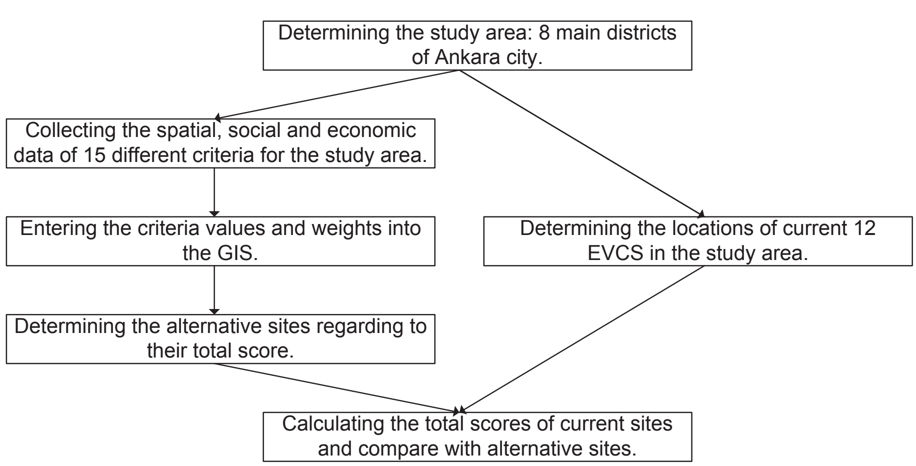

Fig. 10. Flow chart of the application process.

approaches. In the latter, weight values of GIS map layers (criteria) are changed to evaluate the differences in the EVCS suitability map. Finally, weights intervals which do not affect the ranking are investigated.

Effects of different approaches on alternative and current EVCSs: In the initial solution, weights of criteria are determined by fuzzy AHP and alternative stations are ranked by using TOPSIS. Although the GIS-based MCDA methods offer great advantages regarding arrangement of spatial data, the main disadvantage of the method is that the determination of the weight values depend on expert judgments. To prevent this, GIS-based TOPSIS approach which means consideration the criteria weights equally and GIS-based AHP-TOPSIS approach which means consideration the criteria weights certain are also applied to the problem. So, while the proposed approach (PA) includes weighted criteria obtained by fuzzy AHP, alternative approach 1 (AA1) uses equal weighted criteria and alternative approach 2 (AA2) uses crisp AHP. Three different approaches (PA, AA1 and AA2) are applied to three different cases. Considered cases are described below.

Case1: Evaluation of determined 12 alternative stations.

Case2: Evaluation of current 12 stations.

Case3: Evaluation and comparison of the best 6 alternative and current stations.

Figs. 11–13 illustrate the results of each case respectively. As it can be seen from Fig. 11, while PA (weighted criteria) determines AS9 as the best location; AS2 and AS8 are found to be the best location without prioritizing the criteria and with crisp AHP, respectively. Except locations AS1 and AS12, ranking of three approaches are quite different. In three approaches, while AS1 is selected as the worst one, AS12 is selected as fourth one. This analysis shows that weighting the criteria and considering uncertainty make a significant sense on ranking.

One of the aims of this study is also to evaluate the current EVCSs in addition to find new alternative locations for Ankara. To do so, aforementioned three approaches are applied to evaluate and rank the current 12 EVCSs as Case2. According to Fig. 12, while CS12 is selected as the best location, CS8 seems as the worst location in all approaches. If Fig. 9 is investigated clearly, closeness of AS9 and CS12 should be seen obviously. This result also supports considered criteria and applied approaches. In addition to CS12, CS 3 and CS5 are also located in good places. On the contrary, CS2, CS7, CS8 and CS9 which are located in the west of Ankara bring up to the rear in three solutions.

In the last case, the best 6 alternative and current stations are compared based on three approaches (Fig. 13). Results of three approaches show that suggested alternative locations AS2 and AS7

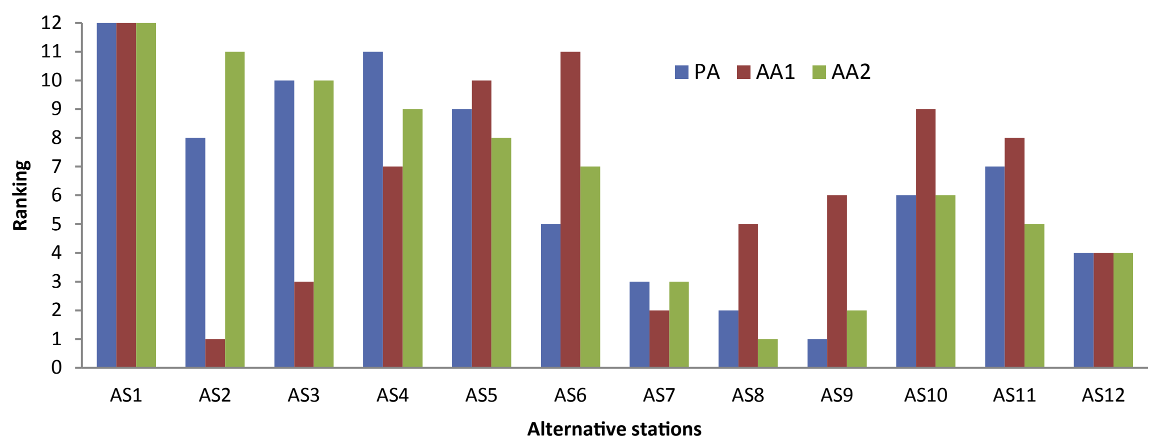

Fig. 11. Ranking of alternative stations based on three approaches (Case1).

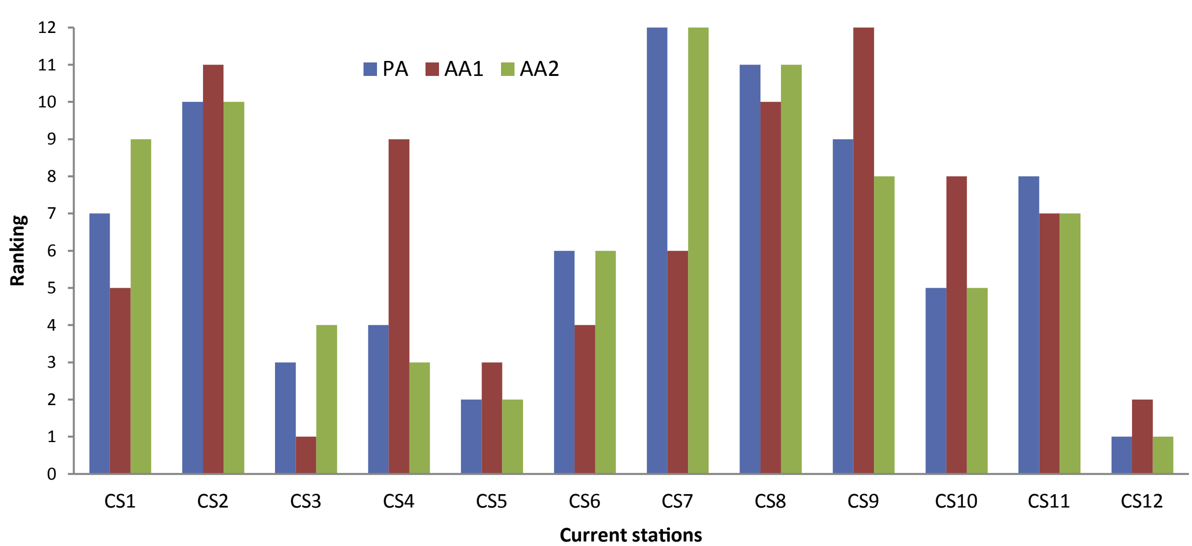

Fig. 12. Ranking of current stations based on three approaches (Case2).

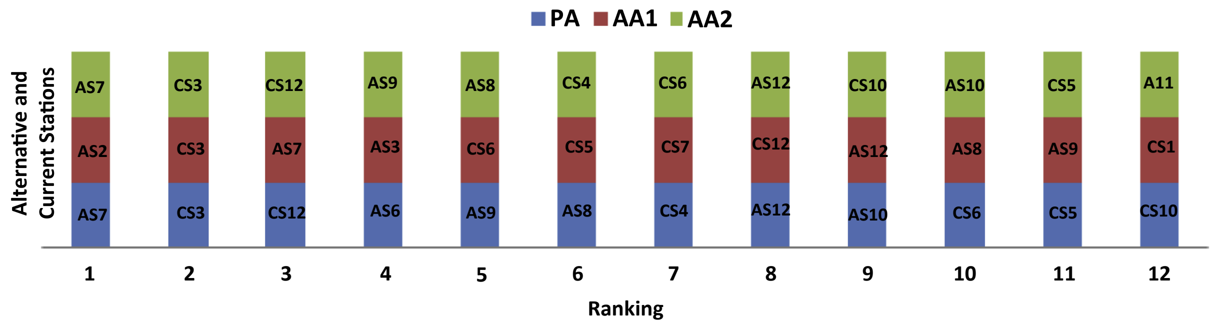

Fig. 13. Ranking of alternative and current stations based on three approaches (Case3).

Table 10
The weights of criteria for each case.

Criteria	Case1	Case2	Case3	Case4	Case5	Case6
C1.1	0.067	0.022	0.109	0.142	0.086	0.094
C1.2	0.067	0.024	0.022	0.029	0.017	0.019
C1.3	0.067	0.057	0.053	0.069	0.042	0.046
C1.4	0.067	0.030	0.028	0.036	0.022	0.024
C1.5	0.067	0.013	0.011	0.014	0.009	0.009
C1.6	0.067	0.043	0.039	0.051	0.031	0.034
C2.1	0.067	0.104	0.094	0.084	0.122	0.081
C2.2	0.067	0.217	0.197	0.175	0.255	0.169
C2.3	0.067	0.142	0.128	0.115	0.166	0.110
C3.1	0.067	0.120	0.109	0.098	0.086	0.142
C3.2	0.067	0.062	0.059	0.053	0.046	0.077
C3.3	0.067	0.108	0.102	0.091	0.080	0.133
C3.4	0.067	0.026	0.020	0.018	0.016	0.026
C3.5	0.067	0.011	0.009	0.008	0.007	0.012
C3.6	0.067	0.021	0.020	0.018	0.016	0.026
Total	1.000	1.000	1.000	1.000	1.000	1.000

are better than the current stations. On the other hand, CS3, that is located in city center of Ankara, takes the second position in all solutions. While PA and AA2 give similar results, AA1 provides quite different ranking. This shows that weighting the criteria leads to a significant impact on ranking. Finally, proposed approaches indicate that current locations of CS3 and CS12 are efficient. However, suggested alternative locations of AS7, AS6 and AS9 are superior to the current locations.

Effects of criteria weights on EVCS suitability map: In this analysis, input factors (weights of criteria) are changed to see what effect this produces on the output. For this reason, sensitivity analysis is done where the weight values of GIS layers (criteria) are changed to evaluate the differences in the EVCS suitability map. Following cases are generated to provide managerial insights. It is noted that sum of weights in all cases is equal to 1. Used criteria weights in all cases are given in Table 10 and changes within the cases are shown in Fig. 14. As can be seen from Fig. 14, the weights of criteria vary from 0.007 to 0255.

Case1: All criteria are weighted equally.

Case2: All criteria are weighted based on crisp AHP.

Case3: All criteria are weighted based on fuzzy AHP.

Case4: Weights of C1.1, C1.2, C1.3, C1.4, C1.5 and C1.6 criteria are increased by 30% while remainder criteria are decreased by 10.5%.

Case5: Weights of C2.1, C2.2 and C2.3 criteria are increased by 30% while remainder criteria are decreased by 21.5%.

Case6: Weights of C3.1, C3.2, C3.3, C3.4, C3.5 and C3.6 criteria are increased by 30% while remainder criteria are decreased by 14%.

The main aim of this analysis is to investigate the suitability zones for an EVCS when the criteria weights are different. The suitability map of the study area was subdivided into the following six intervals [41]: (*i*) very unsuitable, (*ii*) unsuitable, (*iii*) slightly unsuitable, (*iv*) slightly suitable, (*v*) suitable, and (*vi*) very suitable.

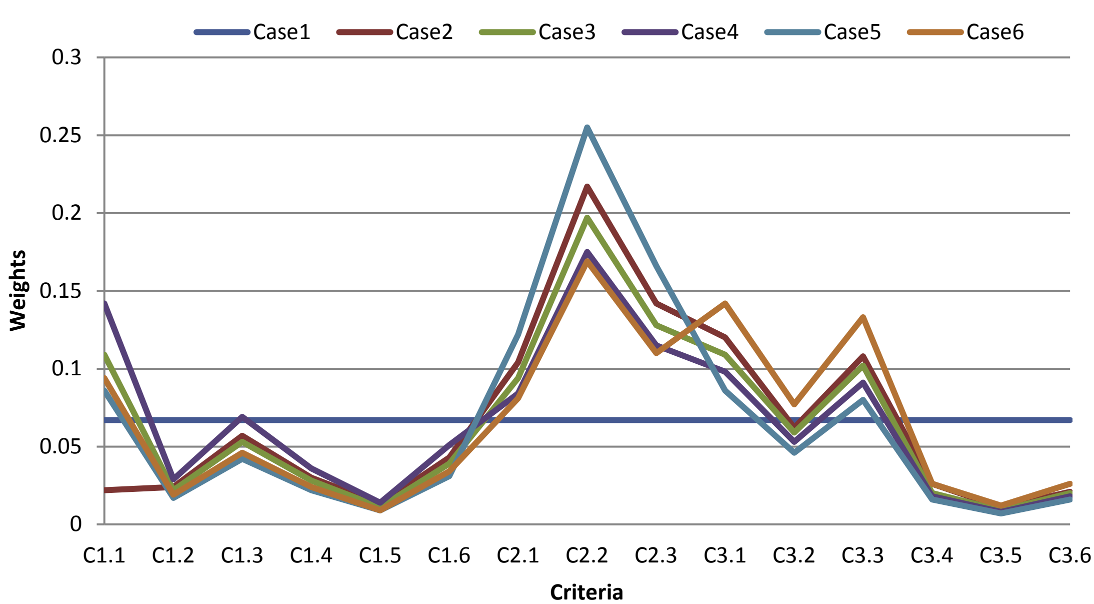

Fig. 14. The sensitivity changes on criteria weights.

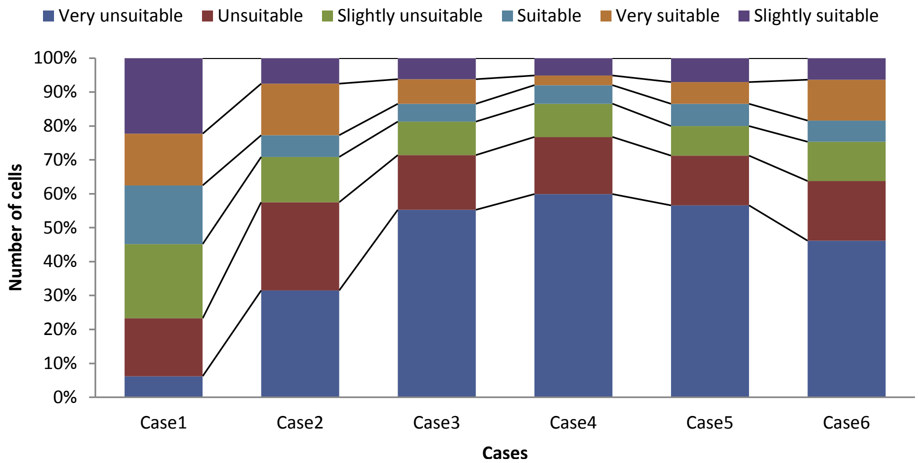

Fig. 15. Number of cells in each case.

The boundaries of the categories in the model are determined by Jenks optimization (natural breaks) for the Case1 [47]. Then, the categories in sensitivity analysis are created by manual interval as the same with base run to make a fair comparison. The number of cells calculated in each category is shown in Fig. 15 and suitability maps regarding to six categories are also shown in Fig. 16. As it can be seen from Fig. 15, while number of very suitable cells is the highest in Case2, minimum number of very suitable cells is observed in Case4. On the other hand, considering the weights under uncertainty (Case2) results less suitable cells than suitable cells obtained by crisp weights (Case3). Number of cells in six categories is distributed proportionally when the weights of criteria are equal (Fig. 16).

On the other hand, if more priority is given to environmental/

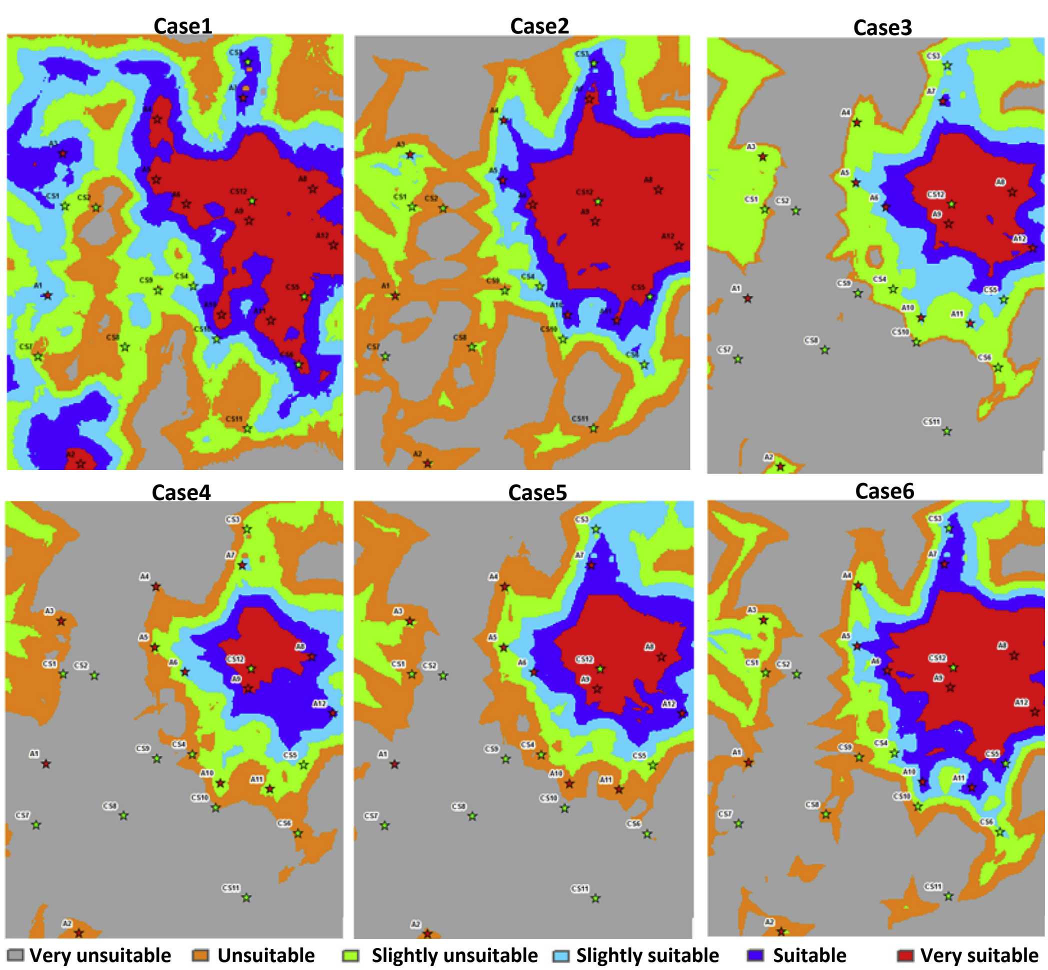

Fig. 16. Suitability map for EVCS siting.

Table 11
Weight stability intervals of the EVCS attributes.

Criterion	Weight (Fuzzy AHP)	Lower Stability Bound	Upper Stability Bound	Interval Value
C1.1	0.109	0.102	0.110	0.106
C1.2	0.022	0.000	0.037	0.019
C1.3	0.053	0.021	0.075	0.048
C1.4	0.028	0.000	0.550	0.275
C1.5	0.011	–	–	–
C1.6	0.039	0.035	0.077	0.056
C2.1	0.094	0.085	0.097	0.091
C2.2	0.197	0.197	0.205	0.201
C2.3	0.128	0.118	0.128	0.123
C3.1	0.109	0.109	0.127	0.118
C3.2	0.059	0.000	0.185	0.093
C3.3	0.102	–	–	–
C3.4	0.020	0.005	0.063	0.034
C3.5	0.009	0.000	0.194	0.097
C3.6	0.020	–	–	–

geographical criteria (Case4) rather than economic (Case5) and urbanity (Case6) criteria, the suitability of the area is decreased. While very suitable area is only 2.85% of the overall map in Case4, this rate is increased to 6.45% and 12.04% in Case5 and Case6, respectively.

Effects of weight intervals on ranking: Criteria weights are calculated based on human judgments; therefore changes in these weights may alter preference rankings. Therefore to improve the confidence in the results and to measure the model's sensitivity to weight changes, the intervals of the weights can be calculated. At these intervals, the first rank of the complete preorder among alternatives does not change. The weight stability intervals of the EVCS evaluation attributes are shown in Table 11.

According to this analysis, for instance, modifying the weight of the “Distance to vegetation” criterion (C1.1.) in the interval [0.102, 0.110] will not affect the positions of alternative ECVSs presented in Table 9. Similarly, weight variations between 0.000 and 0.550 for “Slope of land” (C1.4.) will not change the ranking. On the other hand, the criterion of “EV ownership in the service area” (C2.2.) has the narrowest interval value among others. It means that changing the weight of this criterion with a number greater than 0.008 will change the rank. On the contrary, three criteria namely “Possibility of expansion” (C1.5.), “Proximity to main roads” (C3.3.) and “Distance to other EVCSs” (C3.6.) have the widest interval. It means that any changes on these criteria weights do not affect the final rank.

6. Conclusion and future directions

Transportation efficiency is usually measured by calculating the fuel decrease in the tank; but we assume the fuel will always be there. But if we don't take protective actions we will not be able to calculate the fuel in tanks. Although there are many alternative transportation opportunities that are more environmentally and efficient, many countries including Turkey depend on private automobiles. This situation comes up with more dependence on petroleum products. Nowadays we already have the sustainable technologies to cut off the addiction on oil; the same technology can stabilize the climate, achieve energy independence and maintain our standards of living. In this context, EVs are the nearest solutions to lead us into a more sustainable world in terms of energy. There are both advantages and disadvantages of EVs, so an effective convenient and economic system should be designed to get the best of these vehicles. EVCSs affect the development of this sector directly because low availability of charging infrastructure may throw away the drivers.

To address a sustainable future; Turkey's Ministry of Industry and Trade has been studying on EVs and as the most important extension; the charging stations need to be introduced. EVCS siting is the preliminary stage of EVCS construction, and has a significant impact on the service quality and operation efficiency. Thus, in this paper, a scientific and strategic decision-making methodology is applied to determine new potential locations for EVCSs. To do so, a four step approach is developed. In the first phase of this study, the initial evaluation criteria for optimal siting of EVCSs, which covers three “environmental/geographical”, “economic” and “urbanity” dimensions, and 15 sub-criteria are determined. In the second phase, the geographic information of each indicator is mapped using GIS software to assign an EVCS siting availability score to each site. The “EVCS siting availability score” term used in this study means the weighted average of the site scores on 3 main and 15 sub-dimensions. In last two steps, indicators are prioritized by fuzzy AHP and potential EVCS sites are ranked using TOPSIS techniques, respectively. Using real data from the city of Ankara, we test the validity of our evaluation approach and then compare the best alternative obtained from the proposed method to the current 12 EVCSs located in Ankara. It should be noted that the proposed method is not only applicable to Ankara but all cities that can consolidate the related data for our model. Future studies can be done by using other MCDA techniques as ELECTRE, PROMETHEE or VIKOR. The same methodology can be used on the most crowded cities in Turkey as İstanbul, İzmir, Bursa etc. or the effectiveness analysis can be done for the existing EVCSs. Finally, other technical criteria such as voltage density, power lines, transient stability and power distribution units should be taken into account.

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Nomenclature

l	Lower bound of fuzzy triangular function
m	Moderate point of fuzzy triangular function
u	Upper bound of fuzzy triangular function
S_i-	The separation of each alternative from the ideal solution
S_i+	The separation from the negative ideal solution
C_i*	The relative closeness of the alternative
A_i	with respect to A_+
AA1	Alternative Approach 1
AA2	Alternative Approach 2
AHP	Analytical Hierarchy Process
AI	Absolute Importance
ANP	Analytic Network Process
AS	Alternative Stations
COA	Center of Area
CS	Current Stations
DI	Demonstrated Importance
DM	Decision Makers
EDAŞ	Electricity Distribution Inc. of Ankara
EI	Equal Importance
ELECTRE	Elimination and Choice Translating Reality
EV	Electric Vehicle
EVCS	Electric Vehicle Charging Stations

GIS Geographic Information System
IDW Inverse Distance Weighted
MCDA Multi-Criteria Decision Analysis
NP Non-Deterministic Polynomial
OEM Original Equipment Manufacturer
PA Proposed Approach
PROMETHEE The Preference Ranking Organization Method for Enrichment Evaluation
R&D Research and Development
SI Strong Importance
TOPSIS Technique for Order Preference by Similarity to Ideal Solution
VIKOR Vise Kriterijumska Optimizacija I Kompromisno Resenje
WI Weak Importance

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